REPORT DOCUMENTATION PAGE

Politic Springing budden from the obligation of information is estimated as warmer Door per response, including the time of the OMB NO. 0704-0188 and maintaining the other seconds of propplinging and experting per collection of information, including suggestions for supplinging and experting per collection of information, including suggestions for supplinging and experting per collection of information, including suggestions for supplinging and experting per collection of information, including suggestions for supplinging and supplinging and maintains. Services, Distriction of the Collection of t	and maintaining the data needed,	collection of information	on is estimated to average	1 hour per response including		Form Approved OMB NO. 0704-0188
2. REPORT PATE 4 Nov. 2003 3. REPORT TYPE AND DATES COVERED Final Report for 20 Appl, 1999 to 19 Aug., 200. 4. TITLE AND SUBTITE Electromagnetic Modeling of Quantum-Well Infrared Photodetectors 5. RUNDING NUMBERS 6. AUTHORS: Theodor Tamir, P.1 7. PERFORNING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION REPORT NUMBER 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 11. SUPPLEMENTARY NOTES 12. DISTRIBUTION / AVAILABILITY STATEMENT 12. DISTRIBUTION / AVAILABILITY	1204. Arlington, VA 22222	s for reducing this burd	newing the collection of i	nformation. Send comment	ng the time for rev	iewing instructions, searching existing data
2. REPORT PATE 4 Nov. 2003 3. REPORT TYPE AND DATES COVERED Final Report for 20 Appl, 1999 to 19 Aug., 200. 4. TITLE AND SUBTITE Electromagnetic Modeling of Quantum-Well Infrared Photodetectors 5. RUNDING NUMBERS 6. AUTHORS: Theodor Tamir, P.1 7. PERFORNING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION REPORT NUMBER 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 11. SUPPLEMENTARY NOTES 12. DISTRIBUTION / AVAILABILITY STATEMENT 12. DISTRIBUTION / AVAILABILITY	1. AGENCY USE ON THE	and to the Office of M	lanagement and Budget D	uarters Services, Directorate	for information O	den estimates or any other aspect of this collection of
4. TITLE AND SUBTITLE Electromagnetic Modeling of Quantum-Well Infrared Photodetectors 6. AUTHOR(S): Theodor Tarnir, P.1. 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 6. METOTACH Center Brooklyn, NY 11201 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 11. SUPPLEMENTARY NOTES 12. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. SUPPLEMENTARY NOTES 15. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 16. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 17. SUPPLEMENTARY NOTES 18. SUPPLEMENTARY NOTES 18. SUPPLEMENTARY NOTES 18. DESTRIBUTION / AVAILABILITY STATEMENT 18. ADDRESS(ES) 19. DISTRIBUTION / AVAILABILITY STATEMENT 19. Approved for public release; distribution unlimited, 10. ABSTRACT (Maximum 200 words) 10. SPONSORING / MONITORING 10. ADDRESS(ES) 11. DESTRIBUTION / AVAILABILITY STATEMENT 12. DISTRIBUTION CODE 12. DISTRIBUTION / AVAILABILITY STATEMENT 12. DISTRIBUTION / AVAILABILITY STATEME	THE CALL OF ONLY (Le	ave Blank)	2. REPORT D	aperwork Reduction Project	(0704-0188.) Was	shington, DC 2000s, 1215 Jefferson Davis Highway
Electromagnetic Modeling of Quantum-Well Infrared Photodetectors ATTOMORY APPL FORDERING ORGANIZATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR COMMITTATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR GRANIZATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR COMMITTATION NAME(S) AND ADDRESS(ES) Before Mind or Center Society of Modeling organization or			- KEI OKI DA	AIE	3. REP	OPT Type Ave
Electromagnetic Modeling of Quantum-Well Infrared Photodetectors ATTOMORY APPL FORDERING ORGANIZATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR COMMITTATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR GRANIZATION NAME(S) AND ADDRESS(ES) PROBLEMENT OR COMMITTATION NAME(S) AND ADDRESS(ES) Before Mind or Center Society of Modeling organization or	4 TITLE AND OVE		1 4	NOV. 2003	Final F	Report for 20 A
6. AUTHOR'S) Theodor Tamir, P. I. 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 6. MERCON TAMINE ORGANIZATION NAME(S) AND ADDRESS(ES) 6. MERCON TO COME OF THE PROOF OF T	Flectromannation					report for 20 April, 1999 to 19 Aug., 200:
The Proposition of Paril, P.I. The Proposition of Regardation Name(S) and address(ES) A Performing organization name (S) and address(ES) B. Performing organization name (S) and address(ES) Los Performing organization name (S) and address(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211 1. Supplementary notics The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official experiment of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) Lur work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the yegenerally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-mensional grid geometries. In the applied part (b), we have obtained numerical results for OWIPs under experimental study by accurate. Using this approach, we have also derived design criteria for a wide variety of OWIPs, which were subsequently (IRS) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design guidelines. In addition, we have developed design procedures for new unency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS IOS PERFORMING ORGANIZATION PART (S) AND ADDRESS(ES) 10. NUMBER OF PAGES LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 10. LIMITATION OF ABSTRACT	6 AUTHORITE Modelin	g of Quantum-W	/ell Infrared Dha		5 FIIN	DING NUT
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION REPORT NUMBER 10. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSORING / MONITORING AGENCY REPORT NUMBER 11. SUPPLEMENTARY NOTES 12. LISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 12. Performing of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which encisional grid geometries. In the applied part (b), we have obtained numerical results for OWIPs under experimental study by accurate. Using this approach, we have also derived design guidelines. In addition, we have collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design guidelines. In addition, we have developed design procedures for new unency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 16. PRICE CODE 17. NUMBER OF PAGES 18. SOURCHSTREATION 18. SECURITY CLASSIFICATION ON THIS PAGE ON T	Theodor T		on mareu Photo	detectors	G - #D	AAD10 00 to
o MetroTech Center Brooklyn, NY 11201 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official operation of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 2. ABSTRACT (Maximum 200 words) 2. Work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling foromrance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the president with arbitrary profiles. The theoretical part (a) was carried out for both two-dimensional lamellar and three-lensists at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our laccurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently arrange. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 16. PRICE CODE 17. NUMBER OF PAGES 18. SECURITY CLASSIFICATION 18. SECURITY CLASSIFICATION 19. SECURITY	meduor ramir, pr				——	74D 19-99-1-0126
o MetroTech Center Brooklyn, NY 11201 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official operation of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 12b. DISTRIBUTION ODE 12b. DISTRIBUTION CODE 12c. ABSTRACT (Maximum 200 words) 12d work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling foromance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which entits at the Army Research Laboratory (ARL) and Princeton University, with whom we collaboratemissional landler and three-entitiests at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborate on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently intended with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new unency range. These newer devices are presently in the fabrication stage at ARL. 15c. NUMBER OF PAGES 16. PRICE CODE 17c. NUMBER OF PAGES 18c. SECURITY CLASSIFICATION 18c. SECURITY CLASSIFICATION 19c. SECURIT	PERFORMING ORGANIZ.	ATION NAME (C)			- 1	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211 11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official operation of the Army position, policy or decision, unless so designated by other documentation. 2 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 2 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 3 The views of the author(s) and should not be construed as an official operation of the Army position, policy or decision, unless so designated by other documentation. 1	Polytechnic University	TANIE(3)	AND ADDRESS(ES)			
Security 11201 U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official experiment of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) art work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling formance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by a cacurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs with very subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently with the process of the proceedings of the procedure of QWIPs geometries to be used as two-color detectors, or as spectrometers over a wide unercy range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS DIOMENTAL TRANSFIFED ON THIS PAGE	o MetroTech Center				8. PERF	ORMING ORGANIZATION
P.O. Box 12211 Research Triangle Park, NC 27709-2211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official vegetament of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: distribution unlimited. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: distribution unlimited. 3 DISTRIBUTION CODE 12 b. DISTRIBUTION CODE 13 c. DISTRIBUTION CODE 14 work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling reformance of actual (DWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which ensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by generally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-nessional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by proceed the substance of a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 16. PRICE CODE 17. NUMBER OF PAGES 18. SECURITY CLASSIFICATION OF ABSTRACT ON THIS PAGE ON THIS PAGE	Brooklyn, NY 11201				REPC	ORT NUMBER
P.O. Box 12211 Research Triangle Park, NC 27709-2211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official vegetament of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: distribution unlimited. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: distribution unlimited. 3 DISTRIBUTION CODE 12 b. DISTRIBUTION CODE 13 c. DISTRIBUTION CODE 14 work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling reformance of actual (DWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which ensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by generally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-nessional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by proceed the substance of a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 16. PRICE CODE 17. NUMBER OF PAGES 18. SECURITY CLASSIFICATION OF ABSTRACT ON THIS PAGE ON THIS PAGE	9. SPONSORING / MONITOR	INC ACENTER				
P.O. Box 12211 Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Part views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Part views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official part on the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release: distribution unlimited. 2b. DISTRIBUTION CODE 1c. ABSTRACT (Maximum 200 words) 1c. ABS		THO AGENCY NA	ME(S) AND ADDRE	SS(ES)		
Research Triangle Park, NC 27709-2211 11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Pepartment of the Army position, policy or decision, unless so designated by other documentation. 2 a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 3 ABSTRACT (Maximum 200 words) 12 b. DISTRIBUTION CODE 12 b. DISTRIBUTION CODE 13 provided for public release; distribution unlimited. 4 ABSTRACT (Maximum 200 words) 14 pur work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling reformance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which mensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by dyltical results show very good agreement with the experimental data, thus establishing that oul words will accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently its for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide ununerly range. These newer devices are presently in the fabrication stage at ARL. 15 NUMBER OF PAGES 16 PRICE CODE 16 PRICE CODE 17 NUMBER OF PAGES 18 NUMBER OF PAGES 18 NUMBER OF PAGES 19 SECURITY CLASSIFICATION OF ABSTRACT 19 OF ABSTRACT 19 DISTRIBUTION CODE 19 SECURITY CLASSIFICATION OF ABSTRACT 19 OF ABSTRACT 19 DISTRIBUTION CODE 10 ABSTRACT 10 ABSTRACT 11 APPROACH OF ABSTRACT 12 DISTRIBUTION CODE 13 AB ADDITION CODE 14 ABSTRACT 15 NUMBER OF PAGES	U. S. Army Research	Office		(-0)	10. SPO	NSORING / MONITORING
Research Triangle Park, NC 27709-2211 1. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 11 work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach to evaluate the sy generally be periodic with arbitrary profiles. The theoretical part (a) was carried out for both two-dimensional lamellar and three-institutes at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently ricated with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS TO SECURITY CLASSIFICATION 18. SECURITY CLASSIFICATION OF ABSTRACT ON THIS PAGE UNCLASSIFIED UNCLASSIFIED 10. LIMITATION OF ABSTRACT ON THIS PAGE ON THIS PAGE UNCLASSIFIED	PO Roy 12211	Office			AGE	NCY REPORT NUMBER
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official partment of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 10	Pagage I To				1	
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official perturbation of the Army position, policy or decision, unless so designated by other documentation. 2a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 2b. DISTRIBUTION CODE 1c. ABSTRACT (Maximum 200 words) 1c. ABSTRACT (Maximum 200 word	Research Triangle Pa	rk, NC 27700.	2211			
Pepartment of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 12. DISTRIBUTION CODE ABSTRACT (Maximum 200 words) 13. ABSTRACT (Maximum 200 words) 14. Work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling formance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by eliquical results show very good agreement with the experimental data, thus establishing that our MTL modeling is both powerful ricated with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 18. SECURITY CLASSIFICATION ON THIS PAGE 19. SECURITY CLASSIFICATION OF ABSTRACT 10. UNCLASSIFIED 10. LIMITATION OF ABSTRACT 10. UNCLASSIFIED			4411		1	
Pepartment of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 12. DISTRIBUTION CODE 12. DISTRIBUTION CODE 12. DISTRIBUTION CODE 13. DISTRIBUTION CODE Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) 14. Work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling formance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which ensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by eniotist at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently TPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide unency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE 18. SECURITY CLASSIFICATION ON THIS PAGE 19. SECURITY CLASSIFICATION OF ABSTRACT 10. UNCLASSIFIED 10. LIMITATION OF ABSTRACT 10. UNCLASSIFIED 10. LIMITATION OF ABSTRACT 10. UNCLASSIFIED 10. LIMITATION OF ABSTRACT 10. UNCLASSIFIED	1. SUPPLEMENTARY NOTE:				1301	77 11 -
Pepartment of the Army position, policy or decision, unless so designated by other documentation. 2. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 2. ABSTRACT (Maximum 200 words) 12. DISTRIBUTION (MTL) approach for modeling a rigorous modal transmission-line (MTL) approach for modeling formance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which ensists at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently IPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide unency range. These newer devices are presently in the fabrication stage at ARL. 15. NUMBER OF PAGES 16. PRICE CODE CURITY CLASSIFIED 18. SECURITY CLASSIFICATION ON THIS PAGE UNICLASSIFIED 19. SECURITY CLASSIFICATION OF ABSTRACT UNICLASSIFIED 20. LIMITATION OF ABSTRACT	The views and				1016) (d.11-F1
Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) If work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the ye generally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently IPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide unency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS To Make To PAGES 15. NUMBER OF PAGES 16. PRICE CODE CURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED UNCLASSIFIED 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 10. LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 10. DISTRIBUTION CODE 12. D. LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED 12. D. DISTRIBUTION CODE 12. D. LIMITATION OF ABSTRACT UNCLASSIFIED	Denartment of the	nd/or findings co	Ontained in this ro.			
Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) If work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the supplementation of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently are for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide unency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS Temporary ON THIS PAGE ON THIS PAGE ON THIS PAGE ON THIS PAGE OF ABSTRACT UNCLASSIFIED UNCLASSIFIED 12. DISTRIBUTION CODE **TOTAL CODE** **TOTAL CODE**	population of the Army po	osition, policy o	r decision wal-	port are those of the	author(s) and	d should t
Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) If work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the ye generally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently IPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide unency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS To Make To PAGES 15. NUMBER OF PAGES 16. PRICE CODE CURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED UNCLASSIFIED 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 10. LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 10. DISTRIBUTION CODE 12. D. LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED 12. D. DISTRIBUTION CODE 12. D. LIMITATION OF ABSTRACT UNCLASSIFIED	O DIGITO IN	_	decision, unless	so designated by oth	er document	ration not be construed as an official
Approved for public release; distribution unlimited. ABSTRACT (Maximum 200 words) If work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach to evaluate the year of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently incated with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. 18. SECURITY CLASSIFICATION ON THIS PAGE CURITY CLASSIFICATION ON THIS PAGE 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED 10. DISTRIBUTION CODE 11. DISTRIBUTION OF ABSTRACT 12. DISTRIBUTION OF ABSTRACT 13. DISTRIBUTION OF ABSTRACT 14. DISTRIBUTION OF ABSTRACT 15. NUMBER OF PAGES 16. PRICE CODE 16. PRICE CODE 17. LIMITATION OF ABSTRACT 18. SECURITY CLASSIFICATION 18. SECURITY CLASSIFICATION 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED 10. LIMITATION OF ABSTRACT 14. UNCLASSIFIED	a. DISTRIBUTION / AVAILA	ABILITY STATEM	ENT	<u> </u>	ounten	ation,
ABSTRACT (Maximum 200 words) It work has focused on two principal aspects: (a) developing a rigorous modal transmission-line (MTL) approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach to evaluate the yenerally be periodic with arbitrary profiles, The theoretical part (a) was carried out for both two-dimensional lamellar and three-nestional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently incated with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new usency range. These newer devices are presently in the fabrication stage at ARL. It is security classification It. SECURITY CLASSIFICATION ON THIS PAGE OF ABSTRACT UNCLASSIFIED It. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED III. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED III. LIMITATION OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED III. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	Annessa La		DIA1		12 h Diez	
antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach for modeling antum-well infrared photodetectors (QWIPs) and other optoelectronic devices, and (b) applying this approach to evaluate the formance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently included with specifications that conformed to our design guidelines. In addition, we have developed design procedures for new used as two-color detectors, or as spectrometers over a wide used as two-color detectors, or as spectrometers over a wide stum-well photodetectors action gratings In the applied part (a) was carried out for both two-dimensional lamelar and three-devices are presently in the fabrication stage at ARL. In the applied part (a) was carried out for both two-dimensional lamelar and three-devices are presently in the fabrication stage at ARL. In the applied part (a) was carried out for both two-dimensional lamelar and three-devices are presently in the fabrication stage at ARL. In the applied part (a) was carried out for both two-dimensional lamelar and three-devices are presently in the fabrication stage at ARL. In the applied part (b) applied to the applied part (a) was carried out for both two-dimensional lamelar and three-devices are presently in the fabrication stage at ARL. In the applied part (b) applied to the applied part (a) was carried out for both two-dimensional lamelar and three-devices and three-devices are presently in the fabrication stage at ARL.	Approved for public rele	Approved for public release: distribution at the			1 12 0. DIST	RIBUTION CODE
antum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach for modeling reformance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently IPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide uncy range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS 18. SECURITY CLASSIFICATION 19. SECURITY CLASSIFICATION On THIS PAGE UNCLASSIFIED					1	- TION CODE
antum-well infrared photodetectors (QWIPs) and other optoelectronic devices. and (b) applying this approach for modeling reformance of actual QWIPs. The geometry of the QWIPs may include any number of different dielectric and metallic layers, which nensional grid geometries. In the applied part (b), we have obtained numerical results for QWIPs under experimental study by entities at the Army Research Laboratory (ARL) and Princeton University, with whom we collaborated on a continuous basis. Our accurate. Using this approach, we have also derived design criteria for a wide variety of QWIPs, which were subsequently IPs for focal plane arrays, as well as novel QWIP geometries to be used as two-color detectors, or as spectrometers over a wide uency range. These newer devices are presently in the fabrication stage at ARL. UBJECT TERMS 18. SECURITY CLASSIFICATION 19. SECURITY CLASSIFICATION On This PAGE UNCLASSIFIED	A D Own	distribution	unlimited.			- TON CODE
tromagnetic modeling ntum-well photodetectors action gratings 15. NUMBER OF PAGES	ABSTRACT (Maximum 200 v	words)				
UNCLASSIFIED ON THIS PAGE OF ABSTRACT UNCLASSIFIED ON THIS PAGE UNCLASSIFIED OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	ABSTRACT (Maximum 200 value of the control of the c	o principal aspendetectors (QWIPs. The geometristh arbitrary profit in the applied such Laboratory (good agreement roach, we have a that conformed	cts: (a) developing Ps) and other optory of the QWIPs martiles, The theoretic part (b), we have a ARL) and Princetowith the experimentalso derived design to our design guidents.	ay include any numbical part (a) was carrobtained numerical ron University, with wortal data, thus estable or criteria for a wide	ransmission- and (b) apply per of differe ied out for be results for QV whom we co- lishing that of variety of QV	line (MTL) approach for modeling ying this approach to evaluate the nt dielectric and metallic layers, which oth two-dimensional lamellar and three-WIPs under experimental study by llaborated on a continuous basis. Our MTL modeling is but to the study by the study of the study
UNCLASSIFIED ON THIS PAGE OF ABSTRACT OF ABSTRACT UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED UNCLASSIFIED	ABSTRACT (Maximum 200 various ABSTRA	o principal aspendetectors (QWIPs. The geometristh arbitrary profith arbitrary profith arbitrary profith arbitrary (good agreement roach, we have at that conformed as well as nover devices are profit as the conformation of the	cts: (a) developing Ps) and other optory of the QWIPs may files, The theoretic part (b), we have a ARL) and Princetowith the experimentals of derived design to our design guided QWIP geometric esently in the fabricals.	ay include any numbical part (a) was carrobtained numerical ron University, with wortal data, thus estable or criteria for a wide	ransmission- and (b) apply per of differe ied out for be results for QV whom we co- lishing that of variety of QV	line (MTL) approach for modeling ying this approach to evaluate the nt dielectric and metallic layers, which oth two-dimensional lamellar and three-WIPs under experimental study by llaborated on a continuous basis. Our bur MTL modeling is both powerful WIPs, which were subsequently yeloped design procedures for new ors, or as spectrometers over a wide
540-01-280-5500 UNCLASSIFIED UNCLASSIFIED	ABSTRACT (Maximum 200 varies are the companies of actual QWIF by generally be periodic with the companies of actual QWIF by generally be periodic with the companies at the Army Resear clytical results show very generated with specifications. The for focal plane arrays, using the companies of th	o principal aspendetectors (QWIPs. The geometristh arbitrary profit In the applied in Laboratory (good agreement roach, we have at that conformed as well as nover devices are profit Is. SECURITY	cts: (a) developing Ps) and other optory of the QWIPs may files, The theoretic part (b), we have a ARL) and Princetowith the experimentals of derived design to our design guided QWIP geometric esently in the fabrical CLASSIFICATION.	ay include any numbical part (a) was carrobtained numerical ron University, with wortal data, thus estable criteria for a wide delines. In addition, est to be used as two-ication stage at ARL	ransmission- and (b) apply per of differe ied out for be results for QV whom we co- lishing that covariety of QV we have dev color detector	line (MTL) approach for modeling ying this approach to evaluate the nt dielectric and metallic layers, which oth two-dimensional lamellar and three-WIPs under experimental study by llaborated on a continuous basis. Our bur MTL modeling is both powerful WIPs, which were subsequently veloped design procedures for new ors, or as spectrometers over a wide
	ABSTRACT (Maximum 200 value of the control of the c	o principal aspendetectors (QWIPs. The geometristh arbitrary profit in the applied in the Laboratory (good agreement roach, we have at that conformed as well as nover devices are profit in the conformation of the conformation	cts: (a) developing Ps) and other optory of the QWIPs may files, The theoretic part (b), we have a ARL) and Princetowith the experimentals of derived design to our design guided QWIP geometric esently in the fabrical QWIP geometric esently ese	ay include any number ical part (a) was carrobtained numerical ron University, with vental data, thus estable criteria for a wide delines. In addition, est to be used as two-ication stage at ARL	ransmission- and (b) apply per of differe ied out for be results for QV whom we co- lishing that covariety of QV we have dev color detector	line (MTL) approach for modeling ying this approach to evaluate the nt dielectric and metallic layers, which oth two-dimensional lamellar and three-WIPs under experimental study by llaborated on a continuous basis. Our bur MTL modeling is both powerful WIPs, which were subsequently veloped design procedures for new ors, or as spectrometers over a wide 15. NUMBER OF PAGES 16. PRICE CODE

Prescribed by ANSI Std. 239-18 298-102

A Company of the Comp

FINAL PROGRESS REPORT on Grant No. DAAD19-99-1-0126

Foreword

The following is our final report on the project entitled "Electromagnetic modeling of quantum-well infrared photodetectors," which started on 20 April, 1999, and was completed (after being extended) on August 19, 2003.

The principal aim of this research work was to develop analytical models of periodic configurations that occur mostly in quantum-well infrared photodetectors (QWIPs), as well as in other optoelectronic devices. To strengthen this theoretical study, a close collaboration was maintained with the Dr. K.-K. Choi's group at the Electro-Optics and Photonics Division, Army Research Laboratory, Adelphi, MD, and with Prof. D. C. Tsui's group at the Department of Electrical Engineering, Princeton University, Princeton, NJ. This has enabled us to apply our electromagnetic modeling techniques to a variety of QWIP configurations under active experimental investigation by those two groups. We have thus arrived at interesting and useful explanations of their measurements and have provided guidance in designing their experimental efforts.

The major achievement of our study was the development of a rigorous modal approach for the analysis and design of multilayered QWIP configurations that incorporate arbitrarily shaped periodic contours, and contain materials consisting of lossy dielectric media and metallic conductors. This modal approach provides physical insight into the detection process, on the one hand, and readily performs an accurate evaluation of the photocurrent characteristics, on the other hand. Furthermore, our approach employs transmission-line techniques that serve as a very powerful tool in the engineering design of QWIP structures having specialized and/or desirable characteristics, such as high efficiency, two-color detection capability, narrow or wide bandwidths, etc. As described herein the theoretical basis of our rigorous analytical approach, its associated transmission-line and computational techniques, and its application to a wide variety of QWIP configurations have been published in the professional literature and reported at both general and specialized professional meetings.

Statement of the problem studied

Quantum well infrared photodetectors (QWIPs) generally consist of a quantum well (QW) region inserted between conducting layers that serve as electrodes. Additional layers are also present due to specific device requirements or fabrication purposes. The material forming a OWIP are GaAs and Al₂Ga_{1-x}As, but other materials (such as MgF₂,

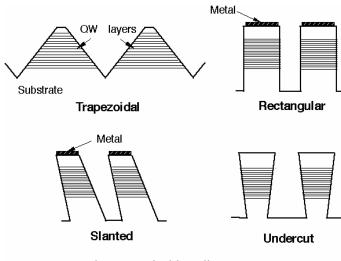


Fig. 1: Typical lamellar QWIPs

epoxy, gold or other conductors) are also part of the complete QWIP device. Because only the incident electric component normal to the QW layers generates photocurrent, it is necessary to incorporate a mechanism that deflects the field into that desired direction. This can be achieved by a grating configuration, which can be above or below the OW laver. 1-3 Alternatively, the QW layer can itself be formed into a periodic structure, thus serving as the required grating.^{4, 5} Because the latter situation is easier to fab-

ricate and exhibits a variety of other advantages, we shall assume that this is the case for illustration purposes.

Several QWIP configurations are shown in Fig. 1, where the periodic portions

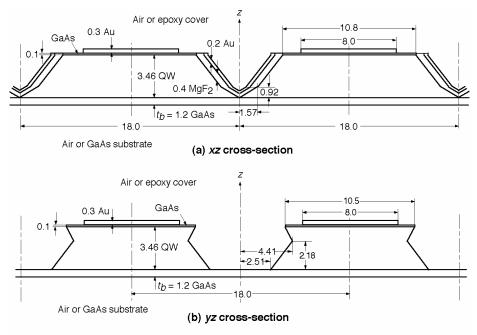


Fig. 2: Grid QWIP with gold and MgF2 layers

consist of rectangular or trapezoidal cells, which may be symmetric or slanted, either in-

tentionally or due to the fabrication (etching) process. Because of their basic lamellar form, these QWIPs can be treated by a simple two-dimensional analysis. A more complex QWIP structure is shown in Fig. 2, where all dimensions are in µm. A large number of layers and different materials are present and the materials include gold (Au), whose electromagnetic behavior is very much different from that of the dielectric materials occupying most of the QWIP configuration. Because the QWIP in Fig. 2 is periodic along both horizontal directions, it forms a grid having trapezoidal xz and hourglass yz cross-sections, which involves a three-dimensional geometry. Obviously, finding the electromagnetic fields due to energy incident on such a configuration poses a formidable boundary-value problem if an accurate electromagnetic field solution is required.

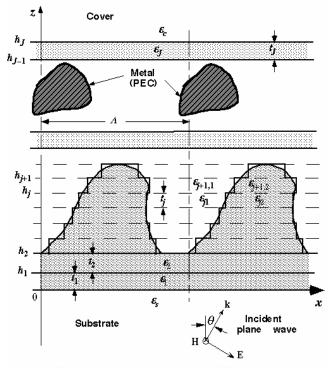


Fig. 3: General geometry of QWIP configurations

To accommodate the large variety of structures illustrated in Figs. 1 and 2, we have explored^{6, 7} the general situation described in Fig. 3, where an electromagnetic field is incident from below into the substrate of a multilayered stack containing periodic elements having arbitrary shapes and materials. The configuration in Fig. 3 allows for arbitrarily shaped periodic regions, and the materials can generally be lossy biaxial dielectrics and/or metallic media, including perfect electric conductors (PECs). As shown here, the geometries in Figs. 1 and 3 are twodimensional (2D) and refer to lamellar QWIP configurations. However, we have also extended our results to three-dimensional (3D) grid configurations, 8 such as that shown in Fig. 2,

by allowing for periodic variations along the y coordinate in Fig. 3.

In all cases, we have developed rigorous analytical solutions that, as described in the next Section, yield the electromagnetic fields at any point in the QWIP structure. By obtaining these fields, it is then possible to derive the power absorption in the QW layers and thus evaluate the photocurrent. This, in turn, determines the quantum efficiency. Other characteristics of the C-QWIP device can similarly be obtained from the field quantities. We have applied these analytical tools to construct computational programs and obtained results for the experimental QWIPs developed by the ARL and Princeton University groups. As described further below, the agreement between our theoretical modeling and their experimental data was very high.

Summary of the most important results

The results achieved by our work fall into two principal categories. The first one is the development of a rigorous analytical solution for the electromagnetic problem posed by the general situation shown in Fig. 3. The second category is the application of this solution to a wide variety of actual QWIP structures. Of these, most have already been (or are expected to be) fabricated and tested by the ARL and Princeton University groups. In this context, we have developed criteria for designing QWIP configurations having novel functions or desirable improved characteristics. Based on these design considerations, new QWIP configurations are either being fabricated for immediate testing, or under consideration for future applications, as further described below.

A. Rigorous electromagnetic modeling

The requisite analytical models for the general periodic structure in Fig. 3 were developed sequentially as follows:

(i) It was first assumed that the materials were dielectrics having complex refractive index, which included metals but not perfect electric conductors (PECs). Periodic regions having arbitrary profiles were subdivided into sufficiently many j = 1, 2, ..., J thin layers, each of which was then approximated by a step-wise periodic region of height t_i and uniform periodic regions having dielectric constants ε_i , ε_{i+1} , ε_{i+2} , ..., as

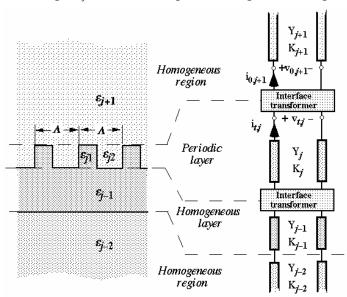


Fig. 4 - Typical portion of a grating geometry and its equivalent network representation

shown in the periodic layer of Fig. 3. By using a rigorous modal approach, the scattering of a plane wave by such a structure can then be described in terms of an equivalent transmission-line network. Specifically, for a relatively simple situation having a periodic layer embedded in regions having homogeneous dielectric media, such a network is shown in Fig. 4.

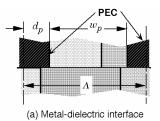
The transmission lines shown here are given by matrix forms of characteristic admittances \mathbf{Y}_j and propagation factors \mathbf{K}_j , whose individual terms represent the various diffracted orders supported by the periodic region. All of these

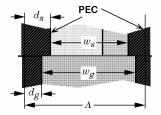
lines are connected in tandem, except that interface transformers are needed at the junctions with the periodic layer. By using units such as that shown in Fig. 4, it is possible to construct the solution to any arbitrary geometry as in Fig. 3.

At this stage of our project, the analysis was restricted to 2D geometries of the lamellar form, but the dielectric media could be uniaxial, so that QW regions were easily accommodated. For these cases, the interface transformers shown in Fig. 4 had

simple matrix relations, which were determined by requiring that the fields of each diffracted order were continuous at the interface.

(ii) The above phase provided a convenient modeling capability for devices containing dielectric media, as well as metals in the form of thin horizontal plates. However, for components consisting of highly conducting metals (e.g., gold or silver) having thicker dimensions, the corresponding computational program converged slowly. To avoid this aspect, the second phase of our study⁷ extended the analysis to geometries that included PECs, which were found to provide excellent numerical results for





(b) Stepped metal-metal interface

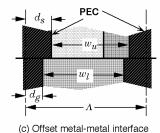


Fig. 5: Typical metallic interfaces

situations involving such highly conducting media. The presence of such PECs does not change the transmission-line aspect depicted in Fig. 4, but it strongly affects the analytical expressions for the interface transformers.

Some of the geometries involving PEC materials are shown in Fig. 5, for which the interface transformations have been analytically derived and applied to specific practical situations. In conjunction with the transmission-line networks illustrated in Fig. 4, these transformations served as templates for computational programs that provided accurate results for the operation of actual lamellar devices whose performance had been experimentally determined. Because the agreement between the experimental data and the theoretical model was very good to excellent, 9, 10 our modal approach can readily serve as a powerful tool for both analysis and design purposes. 11-13

(iii) The preceding discussion has dealt primarily with 2D lamellar configurations. For the more general situation having periodic variations with respect to both *x* and *y* coordinates, e.g., for QWIPs of the grid type in a focal plane array, a 3D geometry is needed. We have therefore extended⁸ our 2D modal transmission-line approach to 3D and have successfully examined several practical situa-

tions. In particular, the complex geometry shown in Fig. 2 was examined and design criteria were established for particular focal-plane arrays. Such arrays have been fabricated and preliminary data have shown good agreement with our theoretical results, but the work is still ongoing and a more thorough comparison between our modeling approach and the actual experimental data remains to be obtained at a later date.

B. Evaluation and design of specific QWIP configurations

The rigorous modeling approach described above was applied to evaluate the performance of experimental QWIPs and to design new configurations, as described below.

(i) The performance of lamellar QWIPs having a slanted trapezoidal profile (as shown in Fig. 1) was evaluated and the theoretical results⁶ showed excellent agreement with the experimental data.⁹ This agreement was especially significant since the QWIP

- performance was analytically predicted without any adjustable parameters, on the one hand, and its geometry involved an asymmetric grating, on the other hand.
- (ii) Design criteria were established for lamellar QWIPs having rectangular gratings in a grid configuration. The top of the rectangular corrugations were covered by a thin gold layer. As in item (i) above, the agreement between the analytical predictions and the experimental results was excellent. Most importantly, we have thus shown that the metal top dimensions play a critical role in maximizing the photocurrent. Specifically, that current peaks if the width of the metal layer is equal to an odd number of half wavelengths in the material. This occurs because the induced current in the metal acts as an electric dipole whose behavior serves as an effective design criterion to optimize performance at desirable wavelengths.
- (iii) Based on the results obtained in item (ii) above, we have established the groundwork for constructing a spectrometer using QWIP elements. $^{11, 12}$ This device consists of channels containing those elements in a grid pattern. The dimensions of the QWIPs in the channels are tailored to provide response peaks at different wavelengths. Design criteria were developed for a spectrometer containing up to 10 such channels and operating in the range $7.5 12.0 \, \mu m$, as well as in a broader $6.0 15.0 \, \mu m$ range. Preliminary experimental results support this concept and its design feasibility.
- (iv) A broad variety of QWIPs having triangular or trapezoidal grating profiles were examined^{6, 12, 13} under different conditions, e.g., with or without metal tops, with air or epoxy covers, placed over thick or thinned substrates, etc. The results have shown that the placement and dimensions of the metal tops may enhance performance in certain cases, but the presence of epoxy cover and/or additional insulating layers (usually, MgF₂ material) could degrade performance. All of these considerations have provided a plethora of design considerations, most of which have been verified experimentally.
- (v) The complex grid structure shown in Fig. 2 for constructing a 1024 x 1024 focal plane array was analyzed and numerical results have shown that it can provide an effective performance over a broad $7.5 11.5 \, \mu m$ wavelength range. This desirable performance is satisfactorily maintained if the structure uses an epoxy cover and has a thin substrate. Hence such a focal plane array can serve as the active component in an infrared imaging camera.
- (vi) Using 3D analysis, we have evaluated the performance of grid QWIPs in which each lattice contains a post incorporating QW layers. The posts may have circular, square or triangular cross-sections, thus leading to different detection efficiencies, which are subject to the symmetry posed by the relevant cross-sections. The results show that the circular posts provide optimum performance and their high symmetry renders them least susceptible to variation in fabrication.

Publications

A. Papers published in peer-reviewed journals

- L. Yan, M. Jiang, T. Tamir and K.-K. Choi, "Electromagnetic modeling of quantum well photodetectors containing diffractive elements," IEEE J. Quantum Electron. **35**, 1870-1877; December 1999.
- L. P. Rokhinson, C. J. Chen, K.-K. Choi, D. C. Tsui, G. A. Vawter, L. Yan, M. Jiang and T. Tamir, "Optimization of blazed quantum grid infrared photodetectors," Appl. Phys. Lett. **75**, 3701-3703; December 1999.
- M. Jiang, T. Tamir and S. Zhang, "Modal theory of diffraction by multilayered gratings containing dielectric and metallic components," J. Opt. Soc. Am. A **18**, 806-820; April 2001. [Errata in J. Opt. Soc. Am. A **19**, 1722 (2002)]
- J. Mao, A. Majumdar, K.-K. Choi, D. C. Tsui, K. M. Leung, C. H. Lin, T. Tamir and G. A. Vawter, "Light coupling mechanism of quantum grid infrared photodetectors," Appl. Phys. Lett. **80**, pp. 868-870; Feb. 2002.
- K.-K. Choi, C.-H. Lin, K. M. Leung and T. Tamir, "QWIP structural optimization," Proc. SPIE **4795**, 27-38; July 2002.
- C.-H. Lin, K. M. Leung and T. Tamir, "Modal transmission-line theory of three dimensional periodic structures with arbitrary lattice configurations," J. Opt. Soc. Am. A 19, 2005-2017; Oct. 2002.
- K.-K. Choi, C. H. Lin, K. M. Leung, T. Tamir, J. Mao, D. C. Tsui and M. Jhabvala, "Broadband and narrow band light coupling for QWIPs," Infrared Phys. Technol. **44**, pp. 309-324; Oct.-Dec. 2003.

B. Papers published in conference proceedings

- K.-K. Choi, C. J. Chen, L. P. Rokhinson, D. C. Tsui, N. C. Das, M. Jhabvala, M. Jiang and T. Tamir, "Corrugated quantum well infrared photodetectors and arrays", Proc. IRIS Meeting on Materials and Detectors, Lexington MA, p. 243; August 1999.
- T. Tamir, M. Jiang and K. M. Leung, "Modal transmission-line theory of composite periodic structures: I. Multilayered lamellar gratings," Proc. 2001 URSI Internatl. Symp. Electromagnetic Theory, Victoria, BC, Canada, pp. 332-334; May 2001.
- C.-H. Lin, K. M. Leung, M. Jiang and T. Tamir, "Modal transmission-line theory of composite periodic structures: II. Three-dimensional configurations," Proc. 2001 URSI Internatl. Symp. Electromagnetic Theory, Victoria, BC, Canada, pp. 335 337; May 2001.

C. Papers presented at meetings

M. Jiang and T. Tamir, "Scattering by multilayered periodic structures containing asymmetric dielectric and metallic components," 1999 USNC/URSI Natl. Radio Science Meeting, Orlando, FL; July 1999.

- M. Jiang, S. Zhang and T. Tamir, "Generalized transmission-line analysis of diffraction by multilayered periodic structures," 2000 Progress in Electromagnetics Res. Symp., Cambridge, MA; July 2000.
- T. Tamir, S. Zhang, M. Jiang and K.-K. Choi, "Electromagnetic modeling of quantum-well infrared photodetectors containing gratings," 2000 Annual OSA Meeting, Providence, RI; October 2000.
- K.-K. Choi, S. V. Bandara, S. D. Gunapala, W. K. Liu, J. M. Fastenau and T. Tamir, "Detection wavelength of InGaAs/AlGaAs MQW and superlattices and electromagnetic modeling of C-QWIPs," Intersubband Transitions in Quantum Wells 2001 Conference, Monterey, CA; Sept. 2001.
- C.-H. Lin, K. M. Leung and T. Tamir, "Scattering by 3D Periodic Structures Containing Metallic Components," 2002 Progress in Electromagnetics Res. Symp., Cambridge, MA; July 2002.
- K.-K. Choi, C.-H. Lin, K. M. Leung and T. Tamir, "QWIP structural optimization," Internatl. Symp. Optical Science and Technol., SPIE 47th Annual Meeting, Seattle, WA; July 2002.
- K.-K. Choi, C.-H. Lin, K. M. Leung, T. Tamir, J. Mao, D. C. Tsui and M. Jhabvala, "Broadband and narrow band light coupling for QWIPs," 2nd Internatl. Workshop on Quantum Well Infrared Photodetectors (QWIPS 2002), Torino, Italy; Oct. 2002.
- K. M. Leung, T. Tamir, C.-H. Lin and K.-K. Choi, "Computer modeling of the electromagnetic properties of quantum-well infrared photodetectors," 2003 Annual Meeting Phys. Soc., Austin, TX; March 2003.
- K.-K. Choi. A. C. Goldberg, K. M. Leung, T. Tamir and M. Jhabavala, "Light coupling for QWIPs." 2003 Annual Meeting Phys. Soc., Austin, TX; March 2003.
- K. M. Leung, C.-H. Lin and T. Tamir, "Numerical modeling of multilayer periodic structures for quantum-well infrared photodetectors," Space-Based EO/IR Surveillance Technol. Conf., Albuquerque, NM; May 2003.
- K. K. Choi, A. C. Goldberg, A. Majumdar, D. C. Tsui, K. M. Leung, T. Tamir, M. Jhabvala, and J. Reno, "Novel QWIP Device Designs" 2003 ARO IR Physics Workshop, Ann Arbor, MI; Sept. 2003.
- K. M. Leung, C.-H. Lin, T. Tamir and K.-K. Choi, "Analysis of metal grating diffraction by models with perfect electric conductors," 2003 Annual OSA Meeting, Tucson, AZ; October 2003.

D. Manuscript submitted but not yet published

K.-K. Choi, K. M. Leung, T. Tamir and C. Monroy, "Light coupling characteristics of corrugated quantum well infrared photodetectors," IEEE J. Quant. Electr., accepted for publication.

List of Participating Scientific Personnel

A. Faculty: Prof. Theodor Tamir, P.I.

Prof. K. Ming Leung.

B. Research Associates: Mr. Shuzhang Zhang

Mr. Lubin Yan

C. Post-Doctoral Fellow: Dr. Mingming Jiang

D. Research Fellow: Dr. Chung-Hsiang Lin (completed a Ph.D. degree in Elec

trical Engineering while working on this project).

Report of Inventions: None

Bibliography

- 1. J. Y. Andersson and L. Lundqvist, "Grating-coupled quantum-well infrared detectors: Theory and performance," J. Appl. Phys. **71**(7), 3600-3610 (1992).
- 2. K. K. Choi, *The Physics of Quantum Well Infrared Photodetectors*, Series in Modern Condensed Matter Physics (World Scientific, Singapore, 1997), Vol. 7, pp. Sect. 6.4, p. 189.
- 3. S. D. Gunapala, S. V. Bandara, A. Singh, J. K. Liu, S. B. Rafol, E. M. Luong, J. M. Mumolo, N. Q. Tran, D. Z.-Y. Ting, J. D. Vincent, C. A. Shott, J. Long, and P. D. LeVan, "640 x 486 long-wavelength two-color GaAs/AlGaAs quantum well infrared photodetector (QWIP) focal plane array camera," IEEE Trans. Electr. Devices 47(5), 963-971 (2000).
- 4. C. J. Chen, K. K. Choi, M. Z. Tidrow, and D. C. Tsui, "Corrugated quantum well infrared photodetectors for normal incident light coupling," Appl. Phys. Lett. **68**(11), 1446-1448 (1996).
- 5. K. K. Choi, C. J. Chen, and D. C. Tsui, "Corrugated quantum well infrared photodetectors for material characterization," J. Appl. Phys. **88**(3), 1612-1623 (2000).
- 6. L. Yan, M. Jiang, T. Tamir, and K. K. Choi, "Electromagnetic modeling of quantum-well photodetectors containing diffractive elements," IEEE J. Quant. Electron. **35**(12), 1870-1877 (1999).
- 7. M. Jiang, T. Tamir, and Z. Zhang, "Modal theory of diffraction by multilayered gratings containing dielectric and metallic components," J. Opt. Soc. Am. A **18**(4), 807-820 (2001).
- 8. C.-H. Lin, K. M. Leung, and T. Tamir, "Modal transmission-line theory of three-dimensional periodic structures with arbitrary lattice configurations," J. Opt. Soc. Am. A **19**(10), 2005-2017 (2002).
- 9. L. P. Rokhinson, C. J. Chen, K.-K. Choi, D. C. Tsui, G. A. Vawter, L. Yan, M. Jiang, and T. Tamir, "Optimization of blazed quantum grid infrared photodetectors," Appl. Phys. Lett. **75**, 3701-3703 (1999).
- 10. J. Mao, A. Majumdar, K. K. Choi, D. C. Tsui, K. M. Leung, C. H. Lin, T. Tamir, and G. A. Vawter, "Light coupling mechanism of quantum grid infrared photodetectors," Appl. Phys. Lett. **80**(3), 868-870 (2002).
- 11. K. K. Choi, C.-H. Lin, K. M. Leung, and T. Tamir, "QWIP structural optimization," Proc. SPIE **4795** (Materials for Infrared Detectors II, R. E. Longshore and S. Savananthan, Editors.), 27-38 (2002).
- 12. K. K. Choi, C. H. Lin, K. M. Leung, T. Tamir, J. Mao, D. C. Tsui, and M. Jhabvala, "Broadband and narrow band light coupling or QWIPs," Infrared Phys. & Tech. 44, 309-324 (2003).
- 13. K.-K. Choi, K. M. Leung, T. Tamir, and C. Monroy, "Light coupling characteristics of corrugated quantum well infrared photodetectors," IEEE J. Quant. Electron., accepted for publication (2003).